

## LCA Methodology

# Country-Dependent Characterisation Factors for Acidification and Terrestrial Eutrophication Based on Accumulated Exceedance as an Impact Category Indicator

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## Abstract

**Background, Aims and Scope.** Several authors have shown that spatially derived characterisation factors used in life cycle impact assessment (LCIA) can differ widely between different countries in the context of regional impact categories such as acidification or terrestrial eutrophication. Previous methodology studies in Europe have produced country-dependent characterisation factors for acidification and terrestrial eutrophication by using the results of the EMEP and RAINS models and critical loads for Europe. The unprotected ecosystem area (UA) is commonly used as a category indicator in the determination of characterisation factors in those studies. However, the UA indicator is only suitable for large emission changes and it does not result in environmental benefits in terms of characterisation factors if deposition after the emission reduction is still higher than the critical load. For this reason, there is a need to search for a new category indicator type for acidification and terrestrial eutrophication in order to calculate site-dependent characterisation factors. The aim of this study is to explore new site-dependent characterisation factors for European acidifying and eutrophying emissions based on accumulated exceedance (AE) as the category indicator, which integrates both the exceeded area and amount of exceedance. In addition, the results obtained for the AE and UA indicators are compared with each other.

**Methods.** The chosen category indicator, accumulated exceedance (AE), was computed according to the calculation methods developed in the work under the United Nations Economic Commission for Europe (UNECE) Convention on Long-range Transboundary Air Pollution (LRTAP). Sulphur and nitrogen depositions to 150x150 km<sup>2</sup> grid cells over Europe were calculated by source-receptor matrices derived from the EMEP Lagrangian model of long-range transport of air pollution in Europe. Using the latest critical load data of Europe, the site-dependent characterisation factors for acidification and terrestrial eutrophication were calculated for 35 European countries and 5 sea areas for 2002 emissions and emissions predicted for 2010. In the determination of characterisation factors, the emissions of each country/area were reduced by various amounts in order to find stable characterisation factors. In addition, characterisation errors were calculated for the AE-based characterisation factors. For the comparison, the results based on the use of UA indicator were calculated by 10% and 50% reductions of emissions that corresponded to the common practice used in the previous studies.

**Results and Discussion.** The characterisation factors based on the AE indicator were shown to be largely independent of the reduction percentage used to calculate them. Small changes in emissions ( $\leq 100$  t) produced the most stable characterisation factors in the case of the AE indicator. The characterisation errors of those characterisation factors were practically zero. This means that the characterisation factors can describe the effects of small changes in national emissions that are mostly looked at in LCAs. The comparison between country-dependent characterisation factors calculated by the AE and UA indicators showed that these two approaches produce differences between characterisation factors for many countries/areas in Europe. The differences were mostly related to the Central and Northern European countries. They were greater for terrestrial eutrophication because the contribution of ammonia emission differ remarkably between the two approaches. The characterisation factors of the AE indicator calculated by the emissions of 2002 were greater than the factors calculated by the predicted emissions for 2010 in almost all countries/sea areas, due to the presumed decrease of acidifying and eutrophying emissions in Europe.

**Conclusions and Recommendations.** In this study, accumulated exceedance was shown to be an appropriate category indicator in LCIA applications for the determination of site-dependent characterisation factors for acidification and terrestrial eutrophication in the context of integrated assessment modelling. In the future, it would be useful to calculate characterisation factors for emissions of separate parts of large countries and sea areas in Europe. In addition, it would also be useful to compare the approach based on the AE indicator with the method of the hazard index, as recommended in the latest CML guidebook.

**Keywords:** Acidification; Europe; characterisation; indicator; integrated assessment modelling; LCIA; life cycle impact assessment; terrestrial eutrophication

## Introduction

The purpose of characterisation in Life Cycle Impact Assessment (LCIA) is to estimate the potential contributions of different environmental intervention (emissions, resource extractions and land use) to different impact categories and to sum the amounts of interventions into a single number within each impact category. An impact category such as acidification or terrestrial eutrophication is a class repre-

senting environmental issues into which Life Cycle Inventory (LCI) results (environmental interventions) may be assigned (ISO 2000).

In characterisation, values of environmental interventions are converted to impact category indicator results by multiplying values of interventions by the corresponding characterisation factors. The determination of characterisation factors within a certain impact category is the core issue in order to produce scientifically-based characterisation results. The determination needs characterisation modelling in which appropriate physical, chemical and biological processes for the selected impact category, linking the LCI results to category indicators, are taken into account. A category indicator is a quantifiable representation of an impact category, being the object of characterisation modelling. Thus, characterisation means that values of environmental interventions are aggregated using the commensurate unit of the category indicator. The category indicator can be defined at any level of the chain of environmental mechanism.

Acidification is one of the most commonly used impact categories in LCA applications. In the earlier stages of LCIA methodology, only site-generic (site-independent) characterisation factors for acidification were used (Heijungs et al. 1992). However, the location of the acidifying emission source can cause different responses in surrounding ecosystems, depending, for example, on local atmospheric conditions and sensitivity of ecosystems subject to deposition from that source (e.g. Hettelingh et al. 1995, Posch et al. 2001). For this reason, there have been research activities to derive site-dependent characterisation factors for acidifying compounds. In the context of the determination of site-dependent characterisation factors, many studies have used the RAINS model developed by the International Institute for Applied System Analysis (IIASA) (Amann et al. 1999). In addition, a similar type of model (EcoSense) developed in ExternE (External Costs of Energy) project (European Commission 1999) has been used together with critical load data (Posch et al. 1997) for the determination of site-dependent characterisation factors. Using the RAINS model, Potting et al. (1998) and Krewitt et al. (2001) using the Ecosense model produced country-specific characterisation factors for acidification in which the category indicator was the change in Area of Unprotected ecosystems (UA) based on critical loads. The calculations were based on a 10% acidifying emission reduction (Potting et al. 1998) or on a 10% emission increase in each country in Europe for a chosen assessment year (Krewitt et al. 2001). Huijbregts et al. (2001) calculated the results in which the indicator was the marginal change in the hazard index of all ecosystems in Europe, where the critical load is actually exceeded (only above scenario) and whether or not the critical load is actually exceeded (above and below scenario). Bare et al. (2003) quantified, in the United States of America, the share of emission depositing on land with the help of atmospheric fate and transport modelling to account for expected source-location-dependent differences in wet and dry deposition. However, they had no critical loads in the calculations and, thus, did not take into account the vulnerability of ecosystems. In terrestrial eutrophication, the determination of country-specific

characterisation factors had been calculated according to the same principles as in acidification (Huijbregts et al. 2001, Krewitt et al. 2001, Potting and Hauschild 2004, see also Potting et al. 2002). Several site-dependent factors and alternative indicators affecting the characterisation factors have been preliminarily discussed from within-country viewpoints (Johansson and Seppälä 2004).

In the case of the UA indicator, Hettelingh et al. (2005) showed that the calculations based on emission changes of minus 50% are generally more reliable for the determination of characterisation factors for acidification than the calculations based on emission changes of minus or plus 10%, because they enable one to reproduce the exact model over a wider range of emission changes. They also produced new country-dependent characterisation factors for acidification using emissions of the year 2000 and the latest critical load database. The method used avoids some shortcomings of the RAINS model, in which critical load exceedances can only be computed with a certain degree of approximation. This calculation improved the characterisation factors of acidification based on the earlier works of the UA indicator (Potting et al. 1998, Potting and Hauschild 2004, Krewitt et al. 2001). However, Hettelingh and his colleagues (2005) recommended that the possibilities to use alternative indicators used in the support of European air pollution policies, such as average accumulated exceedance, should be studied. Pleijel et al. (1997) had drawn the same kind conclusion earlier and calculated the characterisation factors for acidification based on the amount or share of emission depositing on ecosystems calculated for a limited number of Swedish and European regions for which the critical load is exceeded.

Heijungs and Huijbregts (1999) criticised the calculation approach based on the changes in unprotected ecosystem areas, because even small changes in emissions may result in either no increase in the protected areas at all or in (large) jumps in the area protected. This applies to a situation in which only a few critical load functions are given for a grid cell (Posch et al. 2001). To avoid this feature, the difference between current deposition and critical loads should be reflected more strongly in the calculations. Therefore, there is a need to search for a new indicator for the calculations of characterisation factors for acidification and terrestrial eutrophication.

The aim of this article is to address a category indicator accumulated exceedance, for emissions contributing to acidification and terrestrial eutrophication, and to compute the corresponding characterisation factors for European countries and five-sea areas. In addition, the new values are compared with the values produced by the earlier approaches based on the changes in unprotected ecosystem areas.

## 1 Methods

The prerequisite for computing the indicator type 'accumulated exceedance' for a region is the definition and calculation of the exceedance of the critical load of a single ecosystem. In the case of a *terrestrial eutrophication*, the sensitivity of the ecosystem is quantified by the so-called critical load

of nutrient nitrogen,  $CL_{nut}(N)$  [eq/ha/yr] (see Hettelingh et al. 1995). The exceedance of such a critical load [eq/ha/yr] is defined as:

$$Ex(N_{dep}) = N_{dep} - CL_{nut}(N) \quad (1)$$

where  $N_{dep}$  is the sum of  $NO_x$  and  $NH_3$  deposition [eq/ha/yr]. Here, the eq unit corresponds to 1 mol nitrogen.

Since both sulphur and nitrogen depositions contribute to *acidification*, the computation of an exceedance is more involved. The sensitivity of an ecosystem is characterized not by a single number (critical load), but by a so-called critical load function (Fig. 1). Every combination of nitrogen and sulphur deposition lying on or below that function does not cause effects related to acidification, i.e. does not result in critical load exceedance. In the context of acidification, depositions and critical loads are expressed as eq/ha/yr, where 1 eq corresponds to 1 mol proton ( $H^+$ ) released. The exceedance of the acidity critical load (function) for a given pair of depositions ( $S_{dep1}, N_{dep1}$ ) is defined as the sum of N and S deposition reduction required to reach the critical load function by the 'shortest' path, i.e.

$$Ex(N_{dep1}, S_{dep1}) = \Delta N + \Delta S \quad (2)$$

where

- $Ex(.)$  = exceedance of critical load [eq/ha/yr]
- $N_{dep1}$  = total nitrogen deposition in the calculation situation [eq/ha/yr]
- $S_{dep1}$  = total sulphur deposition in the calculation situation [eq/ha/yr]
- $\Delta N$  = nitrogen reduction required to reach the critical load function [eq/ha/yr]
- $\Delta S$  = sulphur reduction required to reach the critical load function [eq/ha/yr]

The accumulated exceedance,  $AE$ , which in this paper has been chosen as an impact category indicator, is defined as the weighted sum of all the critical load exceedances within the area of interest, the weighing factors being the individual ecosystem areas, i.e.

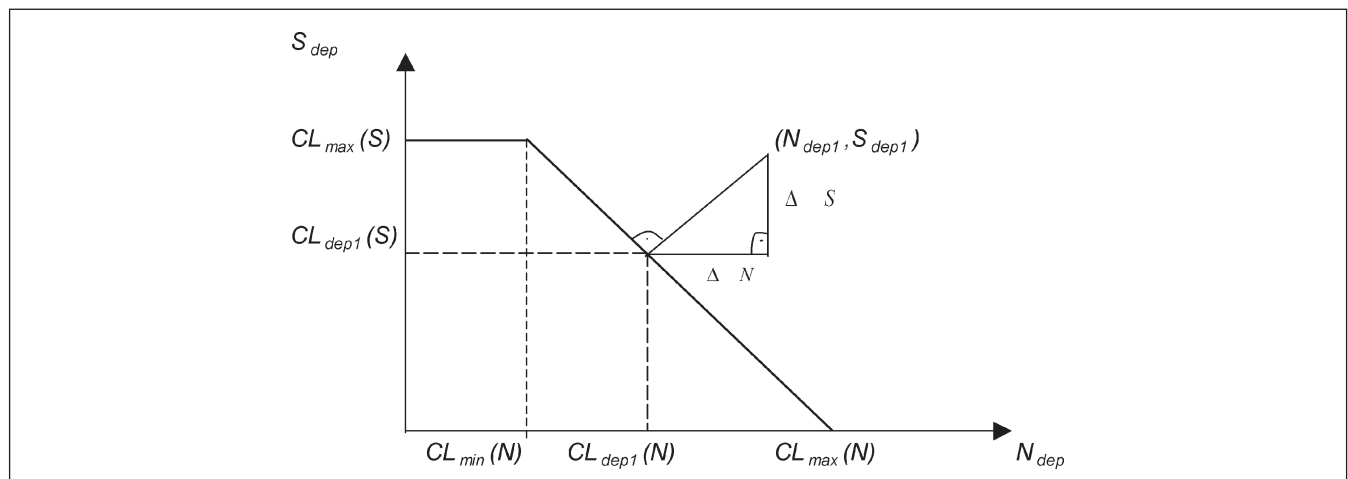
$$AE = A_1 \cdot Ex_1 + \dots + A_n \cdot Ex_n \quad (3)$$

where

- $A_i$  = area of ecosystem  $i$  [ha]
- $Ex_i$  = exceedance in ecosystem  $i$  as defined above [eq/ha/yr]
- $n$  = number of ecosystems within the area of interest

The calculations of  $NO_x$  (expressed as  $NO_2$ ),  $NH_3$  and  $SO_2$  depositions are based on (linear) source-receptor matrices derived from a Lagrangian model of long-range transport of air pollutants within the  $150 \times 150$  km<sup>2</sup> grid cells covering Europe, developed by EMEP (EMEP 1998). The transfer matrices are averages for the meteorological conditions of 12 years (1985–1996) and they relate national emissions (the sources) to the depositions in grid cells (the receptors) (see Schöpp et al. 2003). To make S and N depositions comparable, they are converted to equivalents (moles of charge) per unit area (e.g. eq/ha/yr). This combination of the linearised deposition model with the AE calculations using the full European database on critical loads we call the 'exact model' in the remainder of the paper. Conceptually, the model is the same as the one used by Hettelingh et al. (2005); however, in this work, the model concentrates on the use of accumulated exceedance as impact category indicator and the focus is on small emission changes.

In this paper, we consider the whole of Europe as an 'area of interest', and we use the latest critical load data compiled in the work under the United Nations Economic Commission for Europe (UNECE) Convention on Long-range Transboundary Air Pollution (CLRTAP) (Hettelingh et al. 2004). This data set consists of about 1.5 million individual critical



**Fig. 1:** Schematic figure representing the determination of  $\Delta N$  and  $\Delta S$  for a given pair of depositions ( $N_{dep1}, S_{dep1}$ ) in the context of acidification and a critical load function defined by the maximum critical load of sulphur,  $CL_{max}(S)$ , the minimum critical load of nitrogen,  $CL_{min}(N)$ , and the maximum critical load of nitrogen,  $CL_{max}(N)$  (modified from Posch et al. 2001). Critical loads,  $CL_{dep1}(N)$  and  $CL_{dep1}(S)$ , represent the pair of depositions in critical load function from which there is the shortest path to the given pair of depositions ( $N_{dep1}, S_{dep1}$ )

load (functions) covering the whole of Europe, calculated for different ecosystems such as forests, surface waters, and semi-natural vegetation.

For use in LCIA, the exact model is replaced by an 'additive' (or linearised) model, which is determined by the characterisation factors. These country-dependent characterisation factors for AE as an indicator are defined for every pollutant  $P$  ( $=\text{SO}_2, \text{NO}_2, \text{NH}_3$ ) as:

$$CAE_{P,j} = \frac{\Delta AE_{Europe}^{X-P,j}}{\Delta E_{X-P,j}} \quad (4)$$

where

$$\Delta AE_{Europe}^{X-P,j} = AE_{Europe} - AE_{Europe}^{X-P,j} \quad (5)$$

and

$$\Delta E_{X-P,j} = E_{P,j} - E_{X-P,j} \quad (6)$$

where  $CAE_{P,j}$  is the AE characterisation factor for emissions of pollutant  $P$  in country or sea area  $j$  [keq/t],  $AE_{Europe}$  is the total accumulated exceedance (AE) in Europe due to the emissions in a chosen reference year [keq/yr],  $AE_{Europe}^{X-P,j}$  the total AE in Europe after reducing emissions of pollutant  $P$  in the reference year in country  $j$  by  $X$  (expressed in percent or kt/yr) (with emissions in all other regions unchanged),  $E_{P,j}$  the emissions of pollutant  $P$  in country  $j$  in the reference year [t/yr], and  $E_{X-P,j}$  the emissions of  $P$  in country  $j$  after the reduction of  $X$ .

In addition to the AE indicator, also characterisation factors based on the changes in unprotected ecosystem area (UA) were calculated to make a comparison with the characterisation factors based on changes in AE. The calculations were made analogously to Eqs. (4–6) by replacing AE by UA. Although the calculation methods based on the UA and AE indicators have the same focus, the protection of ecosystem areas based on critical load functions, they measure different things. The starting point for characterisation factors based on the UA indicator is  $UA_{Europe}$ , the total area of unprotected ecosystems based on critical loads in Europe due to the emissions in a chosen reference year. Assume that a given pair of depositions ( $S_{dep1}, N_{dep1}$ ) describe the deposition situation of ecosystem A in grid cell B. After sulphur emission reduction of  $X$ , the situation changed so that the new deposition ( $S_{dep2}, N_{dep2}$ ) is below the critical load function of the ecosystem (see Fig. 1). In the case of the UA indicator, the area of ecosystem A in grid cell B is now excluded from  $UA_{Europe}$ , which means the bigger value for  $\Delta UA_{Europe}^{X-\text{SO}_2,j}$  (c.f. Eq. (4)). If the deposition after the reduction remains above the critical load function, the area of the ecosystem is not eliminated from  $UA_{Europe}$ . Thus, in this case, the reduction is not considered to cause benefits from the point of view of ecosystem protection. However, the AE approach causes the benefits in both cases.

Here, we have chosen 50% reduction of emissions in each country and sea area as a starting point in the determination of characterisation factors for the AE and UA indicators, since the linear model with UA as an indicator is not suitable to evaluate small changes in emissions (Hettelingh et al. 2005). In order to find suitable characterisation factors for each country and sea area in the case of the AE indicator, the calculations were repeated with smaller reduction percentages (or amounts) and the results were compared with the previous results.

The practicality of the characterisation factors was tested with the help of the so-called characterisation error. This error describes the difference between the results calculated by the exact model and the results of the additive model used in characterisation. If the difference is zero, it indicates that pollutants  $\text{SO}_2, \text{NO}_2$  and  $\text{NH}_3$  are independent of each other in the characterisation equation. This is a necessary requirement for the additive model (Dyer and Sarin 1979, see also Seppälä 2003). Thus, the assumption means that the outcome of one pollutant (e.g.  $\text{SO}_2$ ) does not depend on the outcomes of the other pollutants ( $\text{NO}_2$  and  $\text{NH}_3$ ). The reason to test this is due to the fact that characterisation factors for each pollutant had been derived independently from each other.

The starting point for the error calculation is a typical characterisation equation in which the category indicator result of acidification caused by the product system  $a$  is calculated as:

$$I_A(a) = \sum_j (CAE_{\text{SO}_2,j} \cdot E_{\text{SO}_2,j}(a) + CAE_{\text{NO}_2,j} \cdot E_{\text{NO}_2,j}(a) + CAE_{\text{NH}_3,j} \cdot E_{\text{NH}_3,j}(a)) \quad (7)$$

where  $I_A(a)$  is the acidification indicator result of product system  $a$  [keq] and  $E_{P,j}(a)$  the emissions of pollutant  $P$  ( $\text{SO}_2, \text{NO}_2$  or  $\text{NH}_3$ ) of product system  $a$  in country  $j$  [t/yr]. The category indicator result of terrestrial eutrophication,  $I_{TE}(a)$ , is calculated analogously. For the error calculation, product system  $a$  is replaced by country or sea area  $j$ . Thus, in the calculation of the exact model, the emissions of country or sea area  $j$  are reduced by  $X$  amount at the same time, keeping the emissions in the other regions at the values of the reference year. The same emission reductions are used in the calculations of the additive model. From this, the absolute error for country  $j$  with the respect to acidification is obtained by:

$$\begin{aligned} \text{Error}_j = & AE_{Europe} - AE_{Europe}^{X-\text{SO}_2,X-\text{NO}_2,X-\text{NH}_3,j} \\ & - CAE_{\text{SO}_2,j} \cdot \Delta E_{\text{SO}_2,j} - CAE_{\text{NO}_2,j} \cdot \Delta E_{\text{NO}_2,j} \\ & - CAE_{\text{NH}_3,j} \cdot \Delta E_{\text{NH}_3,j} \end{aligned} \quad (8)$$

where  $AE_{Europe}^{X-\text{SO}_2,X-\text{NO}_2,X-\text{NH}_3,j}$  is the total accumulated exceedance in Europe after  $X$  emission reduction of  $\text{SO}_2, \text{NO}_2$  and  $\text{NH}_3$  in country or sea area  $j$  in the reference year (leaving the emissions in the other regions unchanged). The part  $AE_{Europe} - AE_{Europe}^{X-\text{SO}_2,X-\text{NO}_2,X-\text{NH}_3,j}$  in Eq. (8) represents the result of the exact model. Both absolute and percentage errors were



calculated. For the percentage error, the value of the characterisation error was divided by the value of the exact model and the result multiplied by 100.

As reference emissions, we used the national emissions for the year 2002 as well as the predicted emissions for the year 2010, as reported by EMEP (Vestreng et al. 2004). These emissions are also presented in **Appendix 1**.

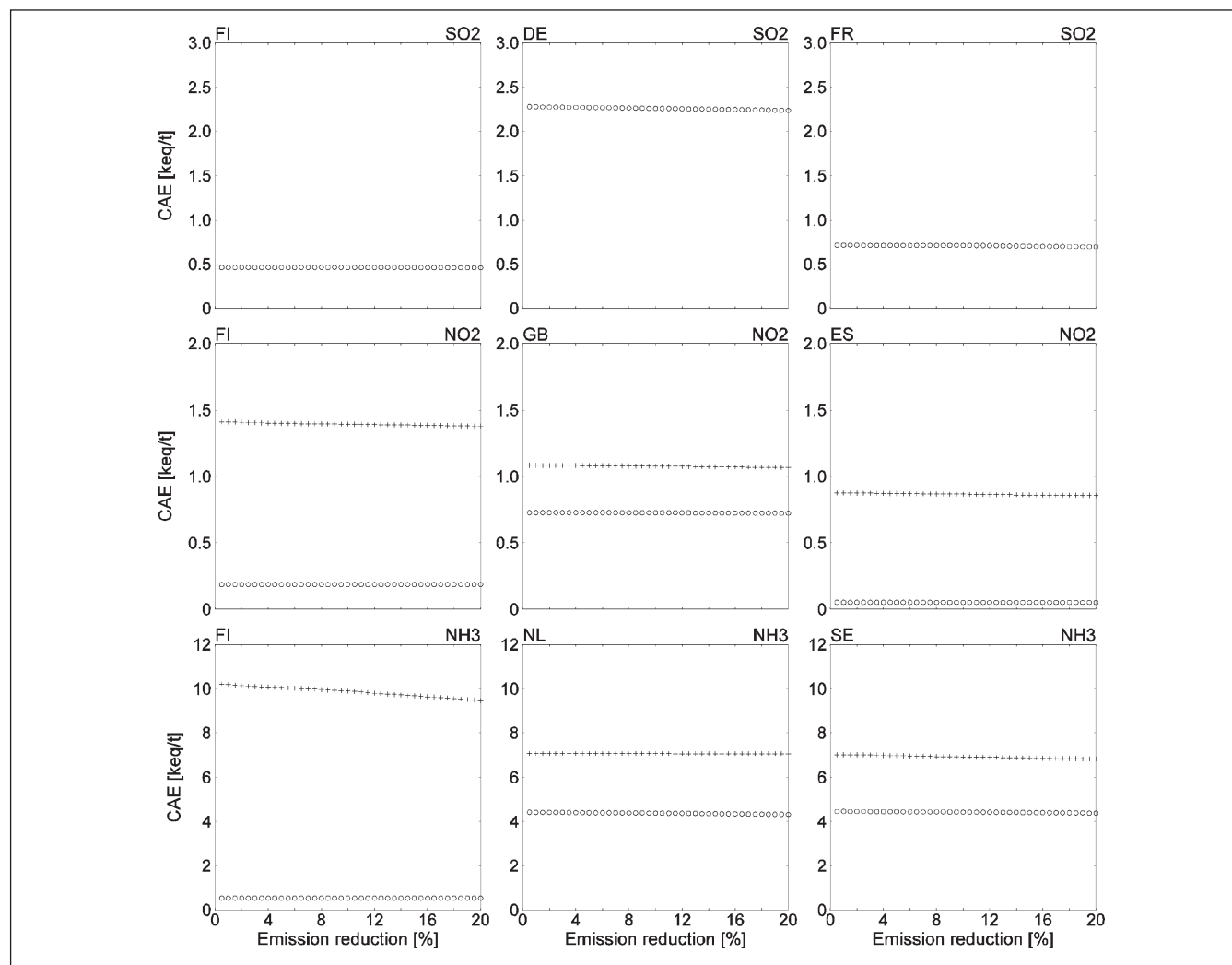
The exact model with the reference emissions for 2002 and 2010 produces values for the total accumulated exceedance for 2002 ( $AE_{Europe}^{2002}$ ) and 2010 ( $AE_{Europe}^{2010}$ ) in Europe. The practicality of the AE based characterisation factors for prediction purposes were also tested with the help of those European reference values. For this purpose, Eq. (9) for assessing the reference value of the year Y ( $AE_{Europe}^Y$ ) is applied (c.f. Hettelingh et al. 2005):

$$AE_{Europe}^Y = AE_{Europe}^{Reference} + \sum_p \sum_j (CAE_{p,j} \cdot \Delta E_{p,j}) \quad (9)$$

where  $AE_{Europe}^{Reference}$  is the total accumulated exceedance in Europe in a reference year (e.g. 2002) and  $\Delta E_{p,j}$  is the change in emission  $P$  between the reference year and the year  $Y$  in country/area  $j$ . Eq. (9) was tested so that  $AE_{Europe}^{2010}$  was calculated using the year 2002 as a reference year and the calculated AE value was compared with the value for the year 2010 obtained by the exact model.

## 2 Results

The calculations based on the use of the AE indicator show that characterisation factors are very similar when they are determined on the basis of emission reductions from 2002 emissions between 0.5% and 20% (in steps of 0.5%), both for acidification and terrestrial eutrophication (Fig. 2). In other words, the characterisation factors are quite independent of the reduction percentage in this interval, whereas, in the case of the UA indicator, characterisation factors are strongly dependent on the reduction percentage, especially where they are small (Hettelingh et al. 2005).



**Fig. 2:** Characterisation factors, using AE as an indicator, for acidification (circles) and terrestrial eutrophication (crosses) for selected regions. Calculations are shown for emission reductions from the 2002 emissions between 0.5% and 20% (in steps of 0.5%) in the respective region (FI = Finland, DE = Germany, FR = France, GB = United Kingdom, ES = Spain, NL = Netherlands, SE = Sweden)

In the context of the AE indicator, small reduction amounts produce stable characterisation factors in both impact categories. In practice, 1 t, 10 t and 100 t reductions of emissions result in the same characterisation factors for each country/area. Even the differences between the results calculated by 1 t reduction of emissions and by 50% reduction of emissions are small (Appendix 2). The characterisation errors of the AE based factors with small reduction amounts

turned out to be non-existent for all countries and for both impact categories (Table 1). Smaller emission reductions results in smaller characterisation errors in the case of the AE indicator. The characterisation error tests how the characterisation model can describe the situations of joint reduction. In practise, this feature is required in LCA applications when two or three acidifying and two eutrophying compounds are considered at the once. Thus, the stability

**Table 1:** Relative and absolute characterisation errors for country-dependent characterisation factors calculated for the AE indicator with a 1 t and a 100 t reduction of emissions in 2002. Negative (positive) values mean that the additive model produces larger (smaller) category indicator results compared to the exact model

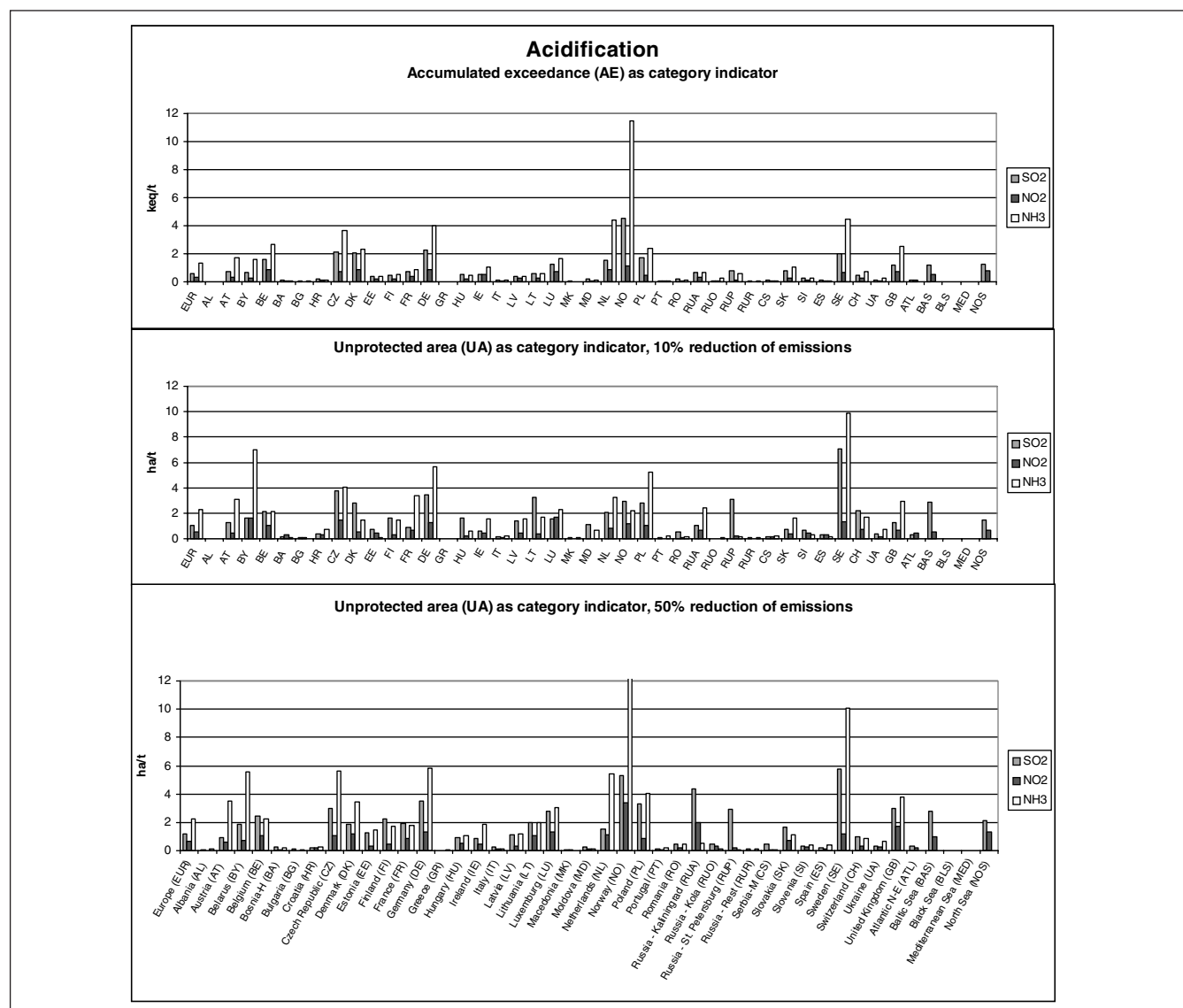
Country	1 t Reduction of Emissions				100 t Reduction of Emissions			
	Acidification		Terrestrial Eutrophication		Acidification		Terrestrial Eutrophication	
	Relative (%)	Absolute (eq/yr)	Relative (%)	Absolute (eq/yr)	Relative (%)	Absolute (eq/yr)	Relative (%)	Absolute (eq/yr)
Albania	0.00	0.00	0.00	-0.02	0.00	-0.04	-0.01	-115.64
Austria	0.00	-0.02	0.00	0.01	-0.01	-25.29	0.00	-0.55
Belarus	0.00	-0.06	0.00	-0.01	0.00	-0.06	0.00	-0.03
Belgium	0.00	-0.01	0.00	-0.02	0.00	-7.26	0.00	0.03
Bosnia and Herzegovina	0.00	0.00	0.00	0.02	0.00	-0.05	0.00	0.01
Bulgaria	0.00	0.00	0.00	-0.01	0.00	-0.05	0.00	-0.05
Croatia	0.00	0.00	0.00	-0.03	0.00	-0.05	0.00	-0.23
Czech Republic	0.00	-0.05	0.00	-0.04	-0.01	-39.51	0.00	-0.39
Denmark	0.00	0.00	0.00	0.00	0.00	-0.08	0.00	-2.18
Estonia	0.00	0.00	0.00	0.01	0.00	-0.06	-0.02	-104.60
Finland	0.00	0.00	0.00	-0.02	0.00	-0.06	0.00	-0.01
France	0.00	0.00	0.00	-0.03	0.00	-0.12	0.00	0.01
Germany	0.00	-0.05	0.00	-0.02	0.00	-24.92	0.00	-0.33
Greece	0.00	0.00	0.00	0.03	0.00	-0.03	0.00	-0.04
Hungary	0.00	0.00	0.00	0.01	0.00	-1.54	0.00	-4.41
Ireland	0.00	0.00	0.00	0.07	0.00	-3.03	0.00	-0.03
Italy	0.00	0.00	0.00	-0.01	0.00	-0.08	0.00	-0.02
Latvia	0.00	0.00	0.00	0.01	0.00	-0.06	-0.21	-1338.40
Lithuania	0.00	0.00	0.00	0.05	0.00	-0.07	-0.01	-128.75
Luxemburg	0.00	-0.03	0.00	-0.03	0.00	-15.14	0.00	-0.00
Macedonia	0.00	0.00	0.00	0.02	0.00	-0.04	0.00	-0.01
Moldova	0.00	0.00	0.00	-0.02	0.00	-0.05	0.00	0.00
Netherlands	0.00	-0.01	0.00	0.03	0.00	-8.19	0.00	-0.02
Norway	0.00	0.00	0.00	0.04	0.00	-0.07	0.00	0.04
Poland	0.00	0.00	0.00	-0.00	-0.01	-37.27	0.00	-37.63
Portugal	0.00	0.00	0.00	-0.03	0.00	-0.01	0.00	0.01
Romania	0.00	0.00	0.00	-0.03	0.00	-0.06	0.00	-0.02
Russia-Kaliningrad	0.00	0.00	0.00	-0.03	-0.01	-18.87	0.00	-10.91
Russia – Kola	0.00	0.00	0.00	-0.01	0.00	-0.00	0.00	-0.02
Russia – St. Petersburg	0.00	0.00	0.00	-0.01	0.00	-0.05	0.00	0.04
Russia – Remaining area	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	-0.01
Serbia and Montenegro	0.00	0.00	0.00	-0.02	0.00	-0.05	-0.01	-115.12
Slovakia	0.00	0.00	0.00	-0.02	0.00	-5.72	0.00	-3.61
Slovenia	0.00	0.00	0.00	0.02	0.00	-0.08	0.00	-0.44
Spain	0.00	0.00	0.00	0.03	0.00	-0.07	0.00	-0.03
Sweden	0.00	0.00	0.00	-0.01	0.00	-16.58	0.00	0.03
Switzerland	0.00	0.00	0.00	-0.02	-0.11	-170.98	0.00	-0.06
Ukraine	0.00	0.00	0.00	-0.00	0.00	-0.05	0.00	-0.05
United Kingdom	0.00	0.00	0.00	0.03	0.00	-7.38	0.00	-0.00
<b>Sea Area</b>								
Atlantic N-E	0.00	0.00	0.00	0.00	0.00	-0.02	0.00	0.00
Baltic Sea	0.00	0.00	0.00	0.00	0.00	-0.02	0.00	0.00
Black Sea	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mediterranean Sea	0.00	0.00	0.00	0.00	0.00	-0.00	0.00	0.00
North Sea	0.00	0.00	0.00	0.00	0.00	-0.05	0.00	0.00

of characterisation factors and the results of characterisation errors show that characterisation factors based on the AE indicator are suitable to describe the effects of small changes in national emissions. The situation is opposite in the case of the UA indicator. Hettelingh and his colleagues (2005) showed that the UA indicator is not suitable for the determination of characterisation factors when small changes in emissions are used for their determination.

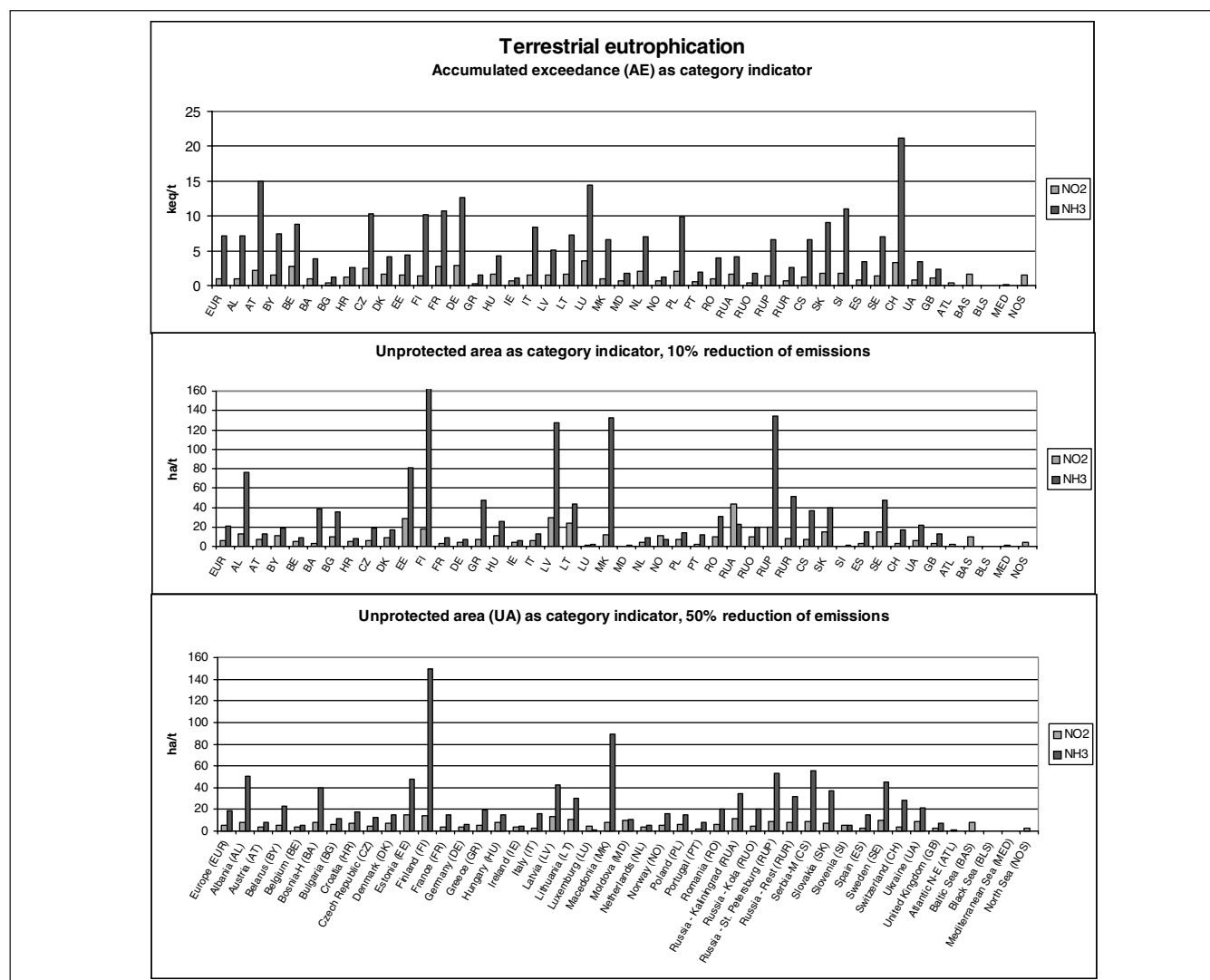
For the above mentioned reasons, the results derived from  $\leq 100$  t reduction of emissions were chosen as the final characterisation factors in the case of the AE approach. The choice is somewhat arbitrary, but has strong bases: the characterisation factors do not change due to 1 t, 10 t and 100 t reductions of national emissions and so the determination of characterisation factors used correspond to the so-called marginal approach that is commonly useful for LCIA applications (see also Section 4). On the other hand, the calculations based on the reductions of 10% and 50% revealed, in

practice, that the characterisation factors selected can describe the effects caused by the bigger reductions of emissions than 100 t. As in **Appendix 2**, it can be seen that several kt reductions of emissions (e.g. in the case of the reductions of 50% in German emissions) produce the same characterisation factors as the 100 t reduction of emissions.

The final characterisation factors based on the AE indicator were used when the characterisation factors based on the AE and UA indicators were compared with each other. The comparison of AE with UA characterisation factors for acidification shows that their distributions over countries/sea areas are quite similar, when the UA indicator was computed with a 50% reduction of emissions (**Fig. 3**). Note that a 50% reduction for the calculation corresponds to the latest recommendation. The equal proportions in the context of both approaches mean that the acidification indicator results of product *a* calculated by the EA and UA based characterisation factors produce the same prioritization (see Eq. (7)).



**Fig. 3:** Country-dependent characterisation factors for acidifying emissions calculated by the AE and UA indicators with the 2002 emissions in Europe. For the AE indicator, the emission reductions were  $\leq 100$  t, whereas 10% and 50% reductions of emissions were used for the calculations of the UA indicator. Note, in the bottom graph, that the Norwegian  $\text{NH}_3$  bar should reach 24.8 ha/t



**Fig. 4:** Country-dependent characterisation factors for eutrophying emissions calculated by the AE and UA indicators in the emission situation of 2002 in Europe. In the context of the AE indicator, the emission reductions used were  $\leq 100$  t, whereas 10% and 50% reductions of emissions were used for the calculations of the UA indicator. Note that the Finnish  $\text{NH}_3$  bar in the centre graph extends to 170 ha/t

The greatest differences can be detected in the results of Belarus, Estonia, Finland, France, Lithuania, Norway ( $\text{NH}_3$ ), St. Petersburg area, Sweden and Baltic Sea. The AE indicator decreases the characterisation factors of those areas compared with the factors of the other countries/areas. It is important to notice that the differences between the factors of different countries/area produced by the AE and UA indicators are greater if the UA calculations are conducted by 10% reduction of emissions (see also Hettelingh et al. 2005). Note that the 10% reduction have been used in the earlier UA studies carried out by Potting et al. (1998) and Krewitt et al. (2001).

The difference between the AE and UA approaches is dramatic in the case of terrestrial eutrophication (Fig. 4). This concerns both UA calculations based on 10% and 50% reductions of emissions. The AE indicator produces greater values for characterisation factors compared with the factors of the other countries. Furthermore, the characterisa-

tion factors for Finland, Estonia, Macedonia and St. Petersburg area are clearly smaller compared with the characterisation factors of other countries in the context of the AE indicator than in the context of the UA indicator. The differences of these two approaches are especially related to the characterisation factors of  $\text{NH}_3$  emissions.

In the case of the AE approach, the characterisation factors calculated by emissions of 2002 and 2010 differ from each other (Table 2). However, in both impact categories, the characterisation factors for almost all countries and sea areas are expected to decrease from 2002 to 2010 due to the predicted reductions of national emissions. According to the exact model, the total accumulated exceedance of acidification in Europe in 2002 was 7,165,220 keq/yr and, in the case of terrestrial eutrophication, 25,518,642 keq/yr. The corresponding values in 2010 were estimated to be 4,238,096 keq/yr and 21,817,431 keq/yr, respectively.



**Table 2:** Country-dependent characterisation factors (keq/t) for acidification and terrestrial eutrophication based on the use of the AE indicator in 2002 and in the predicted emissions for Europe in 2010

Country	Acidification						Terrestrial Eutrophication			
	2002			2010			2002		2010	
	SO <sub>2</sub>	NO <sub>2</sub>	NH <sub>3</sub>	SO <sub>2</sub>	NO <sub>2</sub>	NH <sub>3</sub>	NO <sub>2</sub>	NH <sub>3</sub>	NO <sub>2</sub>	NH <sub>3</sub>
Albania	0.032	0.014	0.021	0.019	0.009	0.012	0.973	7.192	0.612	3.301
Austria	0.711	0.307	1.720	0.437	0.191	0.974	2.199	14.947	2.097	14.639
Belarus	0.688	0.244	1.593	0.726	0.209	1.479	1.464	7.470	1.491	7.691
Belgium	1.579	0.837	2.658	1.114	0.589	1.915	2.720	8.730	2.608	8.499
Bosnia and Herzegovina	0.101	0.055	0.088	0.065	0.035	0.059	1.028	3.855	0.806	1.997
Bulgaria	0.041	0.023	0.040	0.029	0.016	0.027	0.458	1.278	0.795	5.106
Croatia	0.187	0.106	0.151	0.114	0.066	0.097	1.251	2.544	1.141	2.179
Czech Republic	2.118	0.725	3.655	1.255	0.444	1.882	2.520	10.328	2.417	9.728
Denmark	2.043	0.893	2.347	1.623	0.697	1.880	1.660	4.083	1.479	3.407
Estonia	0.369	0.194	0.405	0.469	0.171	0.345	1.483	4.418	1.438	4.214
Finland	0.463	0.186	0.535	0.467	0.159	0.443	1.411	10.215	1.303	8.867
France	0.715	0.396	0.857	0.443	0.261	0.506	2.780	10.755	2.577	9.818
Germany	2.281	0.849	4.000	1.444	0.578	2.823	2.882	12.691	2.774	12.448
Greece	0.012	0.007	0.015	0.008	0.004	0.009	0.300	1.448	0.266	1.157
Hungary	0.542	0.219	0.455	0.330	0.138	0.306	1.686	4.215	1.662	4.176
Ireland	0.558	0.505	1.059	0.411	0.380	0.828	0.622	1.085	0.569	1.020
Italy	0.110	0.065	0.120	0.072	0.041	0.080	1.480	8.363	1.322	7.495
Latvia	0.431	0.235	0.428	0.411	0.196	0.366	1.446	5.209	1.407	4.853
Lithuania	0.569	0.267	0.568	0.492	0.215	0.463	1.583	7.301	1.556	7.117
Luxemburg	1.259	0.730	1.676	0.794	0.475	1.023	3.547	14.491	3.412	13.855
Macedonia	0.035	0.017	0.023	0.021	0.011	0.015	0.997	6.608	0.688	3.129
Moldova	0.176	0.074	0.125	0.146	0.056	0.097	0.749	1.763	0.874	2.324
Netherlands	1.554	0.892	4.414	1.171	0.663	3.496	2.109	7.074	2.010	6.923
Norway	4.524	1.107	11.491	3.579	0.892	9.605	0.674	1.189	0.567	0.894
Poland	1.742	0.498	2.407	0.946	0.302	1.151	2.105	9.868	2.033	9.464
Portugal	0.037	0.035	0.058	0.016	0.022	0.025	0.559	1.906	0.439	1.296
Romania	0.201	0.074	0.124	0.124	0.050	0.085	0.953	3.966	1.226	5.775
Russia – Kaliningrad	0.668	0.335	0.637	0.518	0.250	0.459	1.595	4.173	1.547	4.041
Russia – Kola	0.093	0.046	0.242	0.104	0.042	0.279	0.347	1.835	0.343	2.003
Russia – St. Petersburg	0.782	0.162	0.613	1.701	0.175	0.767	1.332	6.545	1.343	6.590
Russia- Remaining area	0.037	0.021	0.035	0.043	0.020	0.032	0.634	2.638	0.743	3.206
Serbia and Montenegro	0.146	0.058	0.082	0.089	0.036	0.052	1.214	6.639	1.087	4.485
Slovakia	0.786	0.278	1.054	0.463	0.171	0.669	1.834	9.085	1.772	7.899
Slovenia	0.237	0.144	0.270	0.141	0.087	0.149	1.787	11.033	1.693	10.856
Spain	0.108	0.052	0.076	0.052	0.033	0.046	0.877	3.431	0.728	2.736
Sweden	1.993	0.663	4.451	1.648	0.514	3.308	1.337	7.015	1.164	5.361
Switzerland	0.494	0.252	0.747	0.336	0.168	0.520	3.233	21.200	3.021	19.785
Ukraine	0.153	0.066	0.241	0.126	0.051	0.186	0.776	3.458	0.891	3.349
United Kingdom	1.187	0.729	2.501	0.846	0.554	1.734	1.084	2.318	1.000	2.064
<b>Sea Area</b>										
Atlantic N-E	0.164	0.149		0.112	0.106		0.477		0.423	
Baltic Sea	1.201	0.554		0.960	0.426		1.604		1.474	
Black Sea	0.000	0.000		0.000	0.000		0.000		0.000	
Mediterranean Sea	0.006	0.005		0.003	0.003		0.165		0.140	
North Sea	1.296	0.783		1.005	0.601		1.532		1.427	

Eq. (9), for assessing the reference values of different years in Europe, seemed to work quite well on the basis of a test, in which the reference value of the year 2010 was calculated by using the European AE value of the year 2002 obtained by the exact model. For acidification, the calculated error of European AE value in 2010 was -14% and for terrestrial eutrophication the error was -4% when the characterisation factors were determined with  $\leq 100$  t emission reductions. The negative errors mean that Eq. (9) produces larger decreases

for the European accumulated exceedance than the exact model. The calculations were repeated by using the new characterisation factors that corresponded better to the emission changes. The factors were derived from the Appendices 1 and 2 using linear extrapolation. For example, in the case of Germany, SO<sub>2</sub> emissions will be decreased by 161 t/yr from 2002 to 2010 (see Appendix 1). The value corresponds to the reduction of 26% and its characterisation factors will be found between characterisation factors calculated by the

reductions of 10% and 50% (see **Appendix 2**). In the recalculations within acidification, the calculated error of European AE value in 2010 was -10% and, within terrestrial eutrophication, the error was -3%.

In the calculations, Russia was divided into four areas – Kaliningrad, Kola, St. Petersburg and the remaining area of Russia – and characterisation factors were calculated for each area of Russia in order to illustrate how characterisation factors may vary inside a large country. The results show that there is a need to use characterisation factors specific to Kaliningrad, Kola and St. Petersburg if the emission sources can be identified to locate in those areas (see Table 2). Their characterisation factors differ remarkably from site-generic characterisation factors for Russian emissions (in 2002 for acidification SO<sub>2</sub>: 0.213 keq/t NO<sub>2</sub>: 0.030 keq/t and NH<sub>3</sub>: 0.054 keq/t; for terrestrial eutrophication NO<sub>2</sub>: 0.647 keq/t NH<sub>3</sub>: 2.650 keq/t).

#### 4 Discussion

In practice, the accumulated exceedance (AE) has been used in integrated assessment to compute exceedances in support of the 1999 Gothenburg Protocol to the LRTAP Convention dealing with multiple air pollutants and multiple effects (Posch et al. 2001). According to Posch et al. (2001) the greatest advantage of the AE is that it varies smoothly when deposition is varied. Our opinion is that the most important advantage of the AE in the context of LCIA is that the changes in depositions above the critical load can be taken into account in the calculations. However, this feature of the AE stretches the limits of the critical load definition, which assumes that an exceedance implies risk of damage, irrespective of the amount above the critical load. The AE definition assumes a linear damage function (Posch et al. 2001).

The analysis conducted reveals that the characterisation factors derived using the AE indicator will change hardly while changing the amounts of emission reductions. The smaller reductions of emissions lead to the more stable characterisation factors. This differs from the conclusions for the unprotected ecosystem area (UA) indicator where small reductions of emissions lead to unstable characterisation factors (Hettelingh et al. 2005). For applications in the field of integrated assessment, however, where knowledge of changes in a protected ecosystem area is an important endpoint, small reductions in emissions are less relevant. In LCIA, one is particularly interested in characterisation factors which can be applied to small emission reductions. The characterisation factor based on AE provides such an integrated measure, which does not distinguish between the amount and area exceeded.

In the context of AE, the question arises: Should the final factors be based on reductions ≤100 t? Note that the error analysis used does not give an answer to this question. For this reason, the following aspects are pointed out. In LCA, the question is typically about a marginal change in emissions compared with the total national emissions, because the assessment concerns the emissions of functional unit of products (expressed typically as kg emission per tonne product). However, the impact assessment of emissions should not be conducted from the viewpoint of kilograms in the

context of acidification and terrestrial eutrophication. Emissions of products used in LCA are derived from the annual emissions representing the effects of the whole annual production amount. Thus, in order to model the real effects of products, it is valuable to ensure that the characterisation factors can describe the effects caused by the emission range corresponding to the emissions of the whole annual production. In many LCA applications, this means that characterisation factors should describe acidifying and eutrophying emissions representing some hundreds of kilograms or a few tons. However, in the LCA applications, there is very rarely a question about kilo tonnes of emissions of certain countries. For this reason, characterisation factors based on the AE indicator with ≤100 t reduction of emissions are suitable for most LCIA applications. The characterisation factors only differ a little even if the question is the emissions of kilotons used in the determination of characterisation factors. For these extreme applications, the LCIA practitioners can derive characterisation factors from Appendices 1 and 2, using extrapolation in order to get the exact factors (see Section 2).

Due to the reasons mentioned above, on the one hand, the conclusion is that, in the determination of characterisation factors, there is a need to use as small changes in emissions as possible. Thus, this approach corresponds to a so-called marginal approach in order to determine characterisation factors in LCIA (see Udo de Haes et al. 1999). On the other hand, the AE indicator also allows the use of characterisation factors based on the large emission changes so that the impact category indicator results only differ very little from those derived by the small changes of emissions. The stable characterisation factors over a wide range also offer new possibilities to apply the factors for other applications than LCIA. For example, the characterisation factors can be used for the cross-media assessment purposes under Directive 96/61/EC concerning integrated pollution prevention and control (European Commission 2005).

The sensitivity of the characterisation factors calculated by the exact model with the AE indicators to the changes in the national emissions points out the meaning of the accuracy of emissions used as an input in the exact model. It seems, even in Europe, that there exist different views about the emissions (see, for example, the differences between the assessments of the 2000 emissions conducted by Vestreng et al. (2004) and Schöpp et al. (2003)). The lack of consensus means that the results of calculations in a certain year can differ depending on the emission assessments used. However, in the context of the integrated assessment work, there are continuous attempts to increase the quality of emission inputs. When new national emissions or corrections of old emissions are presented, the new calculations carried out by the exact model with updated input data can change the proportions of characterisation factors. This is useful information for LCA practitioners, because relative differences between characterisation factors have influence on the prioritization of different alternatives in the LCA applications. In LCA, there is a need to compare the environmental effects of various process units representing the same time situations, whereas in the field of integrated assessment the

focus is more on the changes in ecosystem quality over time. For this reason, it is useful that experts working in the field of integrated assessment update characterisation factors and a reference value with the exact model with the newest data on national emission inventories when new and approved data become available.

The AE amount of 2002 in Europe produced by the exact model can be directly used as a reference value of the year 2002 for Europe in the normalisation of LCIA. Normalisation is a part of a life cycle impact assessment in which impact category indicator results caused by a product system are divided by the corresponding impact category indicator results (=reference value) caused by a reference system (e.g. activities in a given area over a certain time period) (ISO 2000). The purpose of normalisation is to help the interpretation of the impact category indicator results. If the reference values of the year (e.g. 2002) for Europe are available for different impact categories, such as climate change and acidification normalisation, they can provide a better understanding of the relative proportion or magnitude for each impact category of a product system under investigation. Furthermore, the total accumulated exceedance for 2010 can be used as a reference value of the year 2010 for Europe in normalisation for the prediction purposes.

The determination of characterisation factors was conducted by the exact model that is based on the source-receptor matrices derived from the EMEP Lagrangian model and the newest data on critical loads. In the RAINS models, data on critical loads have been simplified from those used in our exact model. This difference causes one reason why the characterisation factors derived from the exact model will differ from those derived from the RAINS model, although the same indicator and the same emissions as in the input are used in both models. For example, Potting et al. (1998) assessed the robustness of their UA based acidification indicator results by using emission changes from +10% to -50%, with 10% steps, and of -100% in the RAINS model. For selected emission areas, the acidification indicator results due to SO<sub>2</sub> varied with a factor of two while those for nitrogen were relatively stable, providing grounds to underline the reasonable stability of their results. Note that the source-receptor matrices and critical load data used were less detailed than those in the exact model. However, our study showed that UA based acidification indicator results of nitrogen obtained by the exact model can vary by a factor of two or more when the results are based on characterisation factors derived from 10% and 50% reductions of emissions (see the differences between the characterisation factors for Norwegian ammonia emissions, for instance, in Fig. 3).

In this study, site-dependent characterisation factors have been produced as country-dependent factors. In fact, characterisation factors vary inside countries, especially in geographically large countries such as Russia, France and Sweden. The country-dependent approach was used, because only country-to-grid transfer matrices derived from the EMEP Lagrangian model were available. Grid-to-grid matrices could further improve the information provided by characterisation factors derived from them, but are unlikely to be available in the near future on a pan-European scale.

In the LCA terminology, the method based on AE indicator represents the 'only above' approach. The same concerns one version of the hazard index (HI) method developed by Huijbregts and his colleagues (2001). The main difference between these two approaches seems to be that the hazard index method uses a ratio scale in the calculation of exceedance, whereas the AE approach uses the absolute difference. Thus, hazard 'exceedance' for a given pair of depositions ( $S_{dep1}, N_{dep1}$ ) can be defined in the context of acidification as (see Fig. 1)

$$Ha(N_{dep1}, S_{dep1}) = \frac{N_{dep1}}{CL_{dep1}(N)} + \frac{S_{dep1}}{CL_{dep1}(S)} \quad (10)$$

where

- $Ha(.)$  = hazard caused by a deposition [eq/ha/yr]
- $CL_{dep1}(N)$  = critical load of nitrogen for a given pair of depositions ( $S_{dep1}, N_{dep1}$ ) [eq/ha/yr]
- $CL_{dep1}(S)$  = critical load of sulphur for a given pair of depositions ( $S_{dep1}, N_{dep1}$ ) [eq/ha/yr]

In the AE approach, the exceedance  $Ex$  is calculated by the differences  $S_{dep1} - CL_{dep1}(S)$  and  $N_{dep1} - CL_{dep1}(N)$  (see Eq. (1)). In both cases, the values of exceedance are weighted by the areas of ecosystems.

In order to clarify the meaning of ratio scale of the HI method in terms of characterisation factors, there is a need to calculate the corresponding characterisation factors with the same input data and an integrated assessment model. In addition, there is a need to discuss the philosophical/conceptual aspects related to the calculation rules of both methods.

The discussion should also include the hazard index approach in which all deposition situations above and below critical loads in Europe were taken into account. It should be noted that both HI approaches were only applied in the marginal way, i.e. country-dependent characterisation factors for acidification and terrestrial eutrophication were calculated by the derivation in the deposition situation. In this work, the AE approach was studied from the point of view of various emission reductions. Are the conclusions made for the AE indicator also suitable for the HI indicator? This is a question to be explored in depth in future studies.

## 5 Conclusions

The choice of impact category indicator has a great influence on the results of site-dependent characterisation factors for acidification and terrestrial eutrophication. In this paper, we sought to find a robust impact category indicator for acidification and terrestrial eutrophication to be used in LCIA applications. The accumulated exceedance (AE), already used in the context of the integrated assessment work, was found to be an appropriate impact indicator for LCIA purposes. The AE indicator was shown to produce reliable characterisation factors for applications demanding small emission changes in national emissions that are typical for LCIA applications.

The unprotected ecosystem area (UA) indicator has been used in several previous LCIA studies, because it is closely related to the ecosystem health endpoint. The AE indicator has the disadvantage of transcending the limits of the original critical load definition, as it takes into account the amount of exceedance in addition to the area. Its main advantage is that it describes environmental benefits (decreasing deposition load) even if the deposition remains higher than the critical load after emission reductions, i.e. no change in the area of unprotected ecosystems occurs.

We have compiled tables on country-dependent characterisation factors for Europe for acidification and terrestrial eutrophication, separated in respective contributing compounds. These characterisation factors based on the AE indicator are appropriate to various applications, because it produces stable characterisation factors over a wide range of both absolute and relative emission reductions.

In order to search a best practice to determine country-dependent characterisation factors for acidification and terrestrial eutrophication in the future it is worth making a methodical comparison with the hazard index (HI) approach (Huijbregts et al. 2001) recommended in the latest guidebook of CML (Guinée et al. 2002). In addition, an in-depth discussion of the environmental protection aspects of each impact category indicator is required.

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**Appendix 1:** European emissions of sulphur and nitrogen compounds (kt) in 2002 and predicted emissions for 2010 (Vestreng et al. 2004)

	2002			2010		
	SO <sub>x</sub> (as SO <sub>2</sub> )	NO <sub>x</sub> (as NO <sub>2</sub> )	NH <sub>3</sub>	SO <sub>x</sub> (as SO <sub>2</sub> )	NO <sub>x</sub> (as NO <sub>2</sub> )	NH <sub>3</sub>
<b>Country</b>						
Albania	58	29	32	30	27	26
Austria	36	204	53	30	157	56
Belarus	143	137	128	350	266	147
Belgium	153	284	83	105	227	79
Bosnia and Herzegovina	419	55	23	411	53	17
Bulgaria	940	188	56	979	141	124
Croatia	58	77	23	69	91	33
Czech Republic	237	318	72	126	187	63
Denmark	25	200	101	18	146	93
Estonia	88	40	9.1	44	28	11
Finland	82	208	33	63	150	38
France	537	1352	778	404	1051	732
Germany	611	1499	614	450	1176	624
Greece	485	331	73	165	274	54
Hungary	359	180	65	262	132	83
Ireland	96	125	119	34	93	131
Italy	709	1317	442	366	980	421
Latvia	12	41	11	11	30	14
Lithuania	43	51	51	33	41	55
Luxembourg	3	17	7	3	27	4
Macedonia	166	37	16	82	37	15
Moldova	15	25	27	117	62	45
Netherlands	71	406	136	68	327	154
Norway	22	213	22	23	204	27
Poland	1564	805	328	1045	616	328
Romania	912	319	221	669	269	285
Portugal	205	265	93	103	233	69
Russia – Kaliningrad	17	27	7	18	21	10
Russia – Kola	120	160	24	136	148	33
Russia – St. Petersburg	481	75	4	592	73	5
Russia – Remaining area	1513	2303	566	1724	2258	787
Serbia and Montenegro	382	158	79	277	168	69
Slovakia	102	102	29	54	65	32
Slovenia	71	58	19	22	39	20
Spain	1507	1339	379	411	924	382
Sweden	58	242	55	61	193	51
Switzerland	19	94	67	16	74	63
Ukraine	1329	587	378	1146	587	324
United Kingdom	1002	1582	296	364	1113	320
<b>Sea Area</b>						
Atlantic – Remaining N-E	901	1266	0	901	1266	0
Baltic Sea	228	352	0	228	352	0
Black Sea	57	86	0	57	86	0
Mediterranean Sea	1189	1639	0	1189	1639	0
North Sea	453	648	0	454	648	0
<b>Background Country / Area</b>						
Armenia <sup>1</sup>	8	10	25	4	13	25
Azerbaijan <sup>1</sup>	15	43	25	15	43	25
Cyprus <sup>1</sup>	51	22	6	18	22	6
Georgia <sup>1</sup>	6	44	97	9	30	97
Iceland <sup>1</sup>	27	28	3	29	30	3
Kazakhstan <sup>1</sup>	237	50	18	237	50	18
Turkey <sup>1</sup>	2112	951	321	1821	2044	321
Remaining Asian area <sup>1</sup>	869	169	278	830	122	303
North Africa <sup>1</sup>	413	96	235	413	96	235
Natural marine emissions <sup>1</sup>	743	0	0	743	0	0
Volcanic emissions <sup>1</sup>	2000	0	0	2000	0	0

<sup>1</sup> Characterisation factors were not calculated for a country/area. Emissions of the country/area are only used for the background purpose of the impact assessment model.



**Appendix 2:** Country-dependent characterisation factors (keq/t) for acidification and terrestrial eutrophication calculated by different emission reductions in Europe in 2002. The calculations are based on the use of an accumulated exceedance (AE) indicator. Note that the reductions of 1 t and 10 t cause exactly the same characterisation factors as a reduction of 100 t

Country	Acidification									Terrestrial Eutrophication					
	SO <sub>2</sub>			NO <sub>2</sub>			NH <sub>3</sub>			NO <sub>2</sub>			NH <sub>3</sub>		
	100 t	10%	50%	100 t	10%	50%	100 t	10%	50%	100 t	10%	50%	100 t	10%	50%
<b>Country</b>															
Albania	0.032	0.032	0.032	0.014	0.014	0.014	0.021	0.021	0.021	0.973	0.967	0.955	7.186	6.793	4.852
Austria	0.711	0.711	0.709	0.307	0.307	0.306	1.719	1.709	1.589	2.199	2.199	2.195	14.947	14.945	14.923
Belarus	0.688	0.684	0.669	0.244	0.244	0.242	1.593	1.540	1.309	1.464	1.460	1.456	7.470	7.424	6.799
Belgium	1.579	1.576	1.560	0.837	0.835	0.830	2.658	2.651	2.608	2.720	2.719	2.717	8.730	8.725	8.689
Bosnia and Herzegovina	0.101	0.101	0.101	0.055	0.055	0.055	0.088	0.088	0.088	1.028	1.027	1.016	3.855	3.680	3.160
Bulgaria	0.041	0.041	0.041	0.023	0.023	0.023	0.040	0.040	0.040	0.458	0.435	0.420	1.278	1.045	0.996
Croatia	0.187	0.187	0.187	0.106	0.106	0.106	0.151	0.151	0.151	1.251	1.251	1.245	2.544	2.524	2.421
Czech Republic	2.118	2.105	2.056	0.725	0.724	0.719	3.654	3.626	3.474	2.520	2.518	2.508	10.328	10.311	10.115
Denmark	2.043	2.043	2.042	0.893	0.893	0.888	2.347	2.345	2.326	1.660	1.656	1.642	4.082	4.050	3.859
Estonia	0.369	0.369	0.366	0.194	0.194	0.194	0.405	0.405	0.405	1.483	1.478	1.472	4.418	4.372	4.358
Finland	0.463	0.463	0.456	0.186	0.186	0.185	0.535	0.535	0.527	1.411	1.393	1.331	10.215	9.890	8.322
France	0.715	0.713	0.673	0.396	0.395	0.383	0.857	0.821	0.711	2.780	2.775	2.741	10.755	10.645	9.720
Germany	2.281	2.260	2.138	0.849	0.843	0.816	4.000	3.886	3.430	2.882	2.878	2.855	12.691	12.677	12.580
Greece	0.012	0.012	0.012	0.007	0.007	0.007	0.015	0.015	0.015	0.300	0.291	0.266	1.448	1.193	0.816
Hungary	0.542	0.540	0.531	0.219	0.219	0.217	0.455	0.454	0.436	1.686	1.683	1.664	4.214	4.204	4.109
Ireland	0.558	0.558	0.555	0.505	0.505	0.504	1.059	1.044	0.893	0.622	0.620	0.613	1.085	0.942	0.760
Italy	0.110	0.110	0.109	0.065	0.065	0.064	0.120	0.120	0.118	1.480	1.447	1.411	8.363	7.911	7.263
Latvia	0.431	0.431	0.431	0.235	0.235	0.235	0.428	0.428	0.428	1.446	1.433	1.429	5.081	4.984	4.910
Lithuania	0.569	0.569	0.566	0.267	0.267	0.267	0.568	0.563	0.555	1.583	1.576	1.571	7.299	7.140	6.485
Luxemburg	1.259	1.259	1.259	0.730	0.730	0.729	1.675	1.672	1.656	3.547	3.547	3.547	14.491	14.490	14.473
Macedonia	0.035	0.035	0.035	0.017	0.017	0.017	0.023	0.023	0.023	0.997	0.993	0.964	6.608	6.102	4.324
Moldova	0.176	0.176	0.176	0.074	0.074	0.074	0.125	0.125	0.125	0.749	0.749	0.749	1.763	1.763	1.762
Netherlands	1.554	1.552	1.547	0.892	0.891	0.885	4.414	4.379	3.976	2.109	2.108	2.104	7.074	7.070	7.046
Norway	4.524	4.523	4.518	1.107	1.106	1.095	11.491	11.488	11.386	0.674	0.672	0.660	1.189	1.185	1.164
Poland	1.742	1.687	1.389	0.498	0.495	0.485	2.406	2.342	2.169	2.105	2.096	2.067	9.866	9.786	9.422
Portugal	0.037	0.035	0.032	0.035	0.035	0.034	0.058	0.053	0.047	0.559	0.552	0.536	1.906	1.799	1.538
Romania	0.201	0.200	0.192	0.074	0.074	0.074	0.124	0.124	0.123	0.953	0.950	0.915	3.966	3.777	3.210
Russia – Kaliningrad	0.668	0.668	0.666	0.335	0.335	0.335	0.637	0.637	0.637	1.595	1.592	1.589	4.173	4.170	4.160
Russia – Kola	0.093	0.093	0.091	0.046	0.046	0.046	0.242	0.242	0.242	0.347	0.346	0.343	1.835	1.834	1.824
Russia – St. Petersburg	0.782	0.738	0.394	0.162	0.162	0.162	0.613	0.613	0.613	1.332	1.328	1.323	6.545	6.534	6.520
Russia – Remaining area	0.037	0.037	0.037	0.021	0.021	0.021	0.035	0.034	0.034	0.634	0.608	0.476	2.638	2.420	1.732
Serbia and Montenegro	0.146	0.146	0.145	0.058	0.058	0.058	0.082	0.082	0.082	1.214	1.205	1.179	6.635	6.297	4.112
Slovakia	0.786	0.785	0.778	0.278	0.278	0.277	1.054	1.050	1.015	1.834	1.832	1.819	9.085	8.979	8.408
Slovenia	0.237	0.237	0.236	0.144	0.144	0.144	0.270	0.270	0.270	1.787	1.787	1.786	11.033	11.033	11.018
Spain	0.108	0.106	0.099	0.052	0.052	0.051	0.076	0.076	0.074	0.877	0.866	0.820	3.431	3.290	2.716
Sweden	1.993	1.986	1.976	0.663	0.662	0.656	4.452	4.424	4.225	1.337	1.329	1.303	7.015	6.914	6.404
Switzerland	0.494	0.492	0.492	0.252	0.252	0.251	0.745	0.738	0.706	3.233	3.232	3.229	21.200	21.079	20.224
Ukraine	0.153	0.153	0.151	0.066	0.066	0.065	0.241	0.242	0.232	0.776	0.772	0.744	3.458	3.345	2.800
United Kingdom	1.187	1.179	1.127	0.729	0.727	0.706	2.501	2.458	2.217	1.084	1.078	1.049	2.318	2.195	1.704
<b>Sea Area</b>															
Atlantic N-E	0.164	0.163	0.162	0.149	0.149	0.148				0.477	0.476	0.472			
Baltic Sea	1.201	1.198	1.181	0.554	0.553	0.549				1.604	1.594	1.570			
Black Sea	0.000	0.000	0.000	0.000	0.000	0.000				0.000	0.000	0.000			
Mediterranean Sea	0.006	0.006	0.006	0.005	0.005	0.005				0.165	0.164	0.161			
North Sea	1.296	1.295	1.283	0.783	0.783	0.777				1.532	1.531	1.523			